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ABSTRACT

This synthesis of the research on direct manipulation interfaces explores the nature of directness in computer interfaces and demonstrates that the concept of directness is complex, including two gulfs--for execution and evaluation--and two kinds of mappings--semantic mappings and referential distance. Examination of the complexities of the differences among interface styles shows the importance of visibility and sound in the performance of tasks, and a detailed analysis of the general attributes of cognitive artifacts is presented, including a new theoretical construct, the object-symbol. These analyses allow for a deeper understanding of the differences among existing human-machine interfaces and provide the background for the development of a new class of interfaces that promise superior performance. Twenty-four references are listed, and a draft checklist for the design of an artifact is appended. (Author/MES)

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COMPUTATION VIA DIRECT MANIPULATION

Final Report

Contract N00014-85-C-0133

December 1, 1984 to February 29, 1988

Office of Naval Research

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Interfaces to complex equipment can often impose severe difficulties for the user. In part, these difficulties are caused by the abstract nature of the interaction that many modern interfaces present to the operator. A new class of interfaces, the "direct manipulation interface," appears to offer improvements in ease of use and understandability because the abstraction of the normal interface is replaced with what might be called the "model world metaphor," where the user can feel as if the operations are done directly upon the external environment. Research under this contract examined in detail the nature of directness in the use of computer interfaces. The research demonstrates that the concept of "directness" is a complex one, involving at least four different aspects of the interface, including two gulfs, one for execution and one for evaluation, and two different kinds of mappings: semantic mappings and referential distance. The experimental and theoretical work reported under this contract examines the complexities of the

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differences among interface styles, demonstrates the importance of visibility and sound in the performance of tasks, and presents a new, detailed analysis of the general attributes of cognitive artifacts, including an important new theoretical construct: the object-symbol. These analyses allow for a deeper understanding of the differences among existing human-machine interfaces and provide the background for the development of a new class of interfaces that promise superior performance.

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Computation via Direct Manipulation

DONALD A. NORMAN and EDWIN L. HUTCHINS

INTRODUCTION

This is the final progress report for contract N00014-85-C-0133, NR 667-541, *Computation via Direct Manipulation: Cognitive Science Construction Methods for Computational Systems, Expert Assistants, and Graphical Direction of Complex Systems,* with the Personnel and Training Research Programs of the Office of Naval Research (also known, informally, as "the Bridges Contract"). This contract was performed jointly by members of the Institute for Cognitive Science at the University of California, San Diego (UCSD) and members of the Intelligent Systems Group of the Navy Personnel Research and Development Center (NPRDC). Key members of the research team were Donald Norman and David Owen from UCSD, Jim Hollan, Ed Hutchins, and Miriam Schustack from NPRDC, and Colleen Seifert, an Office of Naval Technology and American Society for Engineering Education Postdoctoral Fellow. The total research group over the course of the contract period consisted of the following individuals:

Larry Bierma (NPRDC)
Bill Gaver (UCSD and Apple Computer)
Michael Goeller (UCSD)
Jim Hollan (NPRDC: resigned in January 1987 to become technical director of the Human Interface Program at the Microelectronics and Computer Technology Corporation [MCC; Austin, Texas])
Ed Hutchins (NPRDC, then UCSD)
Masumi Ishikawa (UCSD, visiting from MITI Electrotechnical Laboratories, Japan).
Tim McCandless (NPRDC: resigned in January 1987 to join the Human Interface Program at MCC)
Barbara Morris (UCSD)
Donald Norman (UCSD)
Mark Rosenstein (NPRDC: resigned in January 1987 to join the Human Interface Program at MCC)
David Owen (UCSD)
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Colleen Seifert (Office of Naval Technology and American Society for Engineering Education Postdoctoral Fellow at NPRDC)
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Larry West (UCSD)
Melissa Monty Whittaker (UCSD and Xerox)
Jiajie Zhang (UCSD)

DIRECT MANIPULATION INTERFACES

Computers are clearly the most powerful and most flexible information processing tools ever. Given the dominant perspective in cognitive science that human cognition is best thought of as a form of information processing or computation, it seems obvious that computers have a greater potential than any other technology to enhance or augment human cognitive capabilities. But the problem of getting the human information processing system to work with the machine has not been easily solved. Interacting with computers often seems difficult and frustrating. Traditionally, in order to get a computer to do anything useful, one needed to learn a language in which the computer could be given instructions.

In recent years, primarily in the wake of the advent of new input/output technologies, a vaguely defined set of characteristics parading under the banner of "direct manipulation" (Shneiderman, 1982) promised to make the computational power of computers more easily accessible. We set out to discover whether and how this might be true. We started off with a general analysis of the characteristics of direct manipulation (DM) interfaces (see Hutchins, Hollan, & Norman, 1986), and this study led us to a series of studies aimed at understanding how computers can augment human cognitive abilities.

One of the most important products of our research has been a new understanding of the context that surrounds our original goals. As our understanding of this context grew, topics that had not seemed closely related to the issues of DM began to seem very relevant indeed. The theme expressed in the formal title of the contract — direct manipulation — emphasizes the central focus: the study of tools that might be easier to understand and easier to use than conventional ones. But as we pursued this analysis, we discovered that to do the study properly we needed to understand the wider range of issues surrounding the ways that people perform their tasks. This research project has therefore broadened to consider a number of the overall issues relevant to the study of human action and the interactions between people and designed artifacts. This has led to a number of related studies:

- *The experimental comparison of systems that have different properties.* This was an experimental analysis of the difference in acquisition and performance of these two different styles of interaction with two systems for creating drawings that were formally equivalent in power (Schustack, in preparation).

- *The development of a direct manipulation system for the analysis of statistical data.* This programming development and analytical study allowed us to develop the implications of such systems on behavior (Owen, 1987, 1988).

- *Studies of the role of naturalistic sound.* Systems that are "direct" provide rich and immediate feedback about the actions and system state. Sound can provide information about the nonvisible aspects of the interaction

and of the workings of the system. But for the sound to provide a rich source of information in a way that is readily interpretable, we discovered that it must be "naturalistic," related in natural ways to the kind of physical interactions users expect from their conceptual models of the system (Gaver, 1986, 1988).

- *The development of design rules.* The various studies of this research contract, combined with our earlier studies of errors in human action (work supported by previous ONR contracts), led to the recent book *The Psychology of Everyday Things*, which provides a summary of the issues and suggestions for design (Norman, 1988).

- *The study of socially distributed cognition.* One new important direction of research has been developed through the study of naturally situated cognition and, in particular, the study of the interactions and cognitions of the members of navigation teams aboard large navy ships (Hutchins, in press; Seifert & Hutchins, 1988). The computations undertaken by a navigation team are so completely embedded in the manipulation of computational tools that even the participants are often unaware of the fact that they are doing computations: The specialized navigational instruments provide a setting in which all the computation happens outside the people who perform it.

These studies combine to form a cohesive attack on the understanding of four essential aspects of performance on tasks:

1. Detailed analyses of the tasks.

2. Analyses of the individuals, including their information processing structures, their knowledge structures, and the kinds of conceptual and mental models that they form.

3. The role of social interaction in the performance of cooperative work, especially how social groups share responsibilities in the performance of a task, including the fact that many of the individuals may have only limited understanding of the complete task domain and that training and error correction are often integral parts of social task performance, and help dictate a number of the ways in which the task is structured and performed.

4. The study of the tools themselves, those artifacts that aid human cognition.

The four topics provide the theme for the analyses presented in this report. In this report, rather than provide a simple review of the published papers, books, and technical reports that have come from this project, we provide a new synthesis. This report, therefore, is more than just a summary: It is a new technical formulation of the issues, one that we believe provides promise for the understanding of existing intelligent systems, suggestions for the development of new systems, and a framework for future research efforts.

The Gulfs of Execution and Evaluation

In doing a task with an artifact, whether it be computer or some simpler technology, we can identify several aspects of the performance that affect the way in which the task gets done. When a person does an action, there are two major aspects — the execution side of the action and the evaluation of the resulting world-state. In our earlier paper (Hutchins, Hollan, & Norman, 1986), we described two gulfs that lie between the user and the artifact. First consider the *gulf of execution*, which lies between the user's goals and the possible

actions on the interface. In order to use the device, the user must span this gulf by determining which actions on the interface will accomplish the current goals and by performing those actions. The task of figuring out what to do and then doing it takes effort. If it takes a lot of effort, we say the gulf is wide. The other gulf is the *gulf of evaluation*. It is spanned by perceiving, interpreting, and evaluating the state of the world and comparing it to the desired or expected (goal) state (Figure 1). We argued that one of the most critical issues in interface design is the minimization of effort required to bridge these gulfs. That is, we would like to make the gulfs narrow. But what is it that makes them wide?

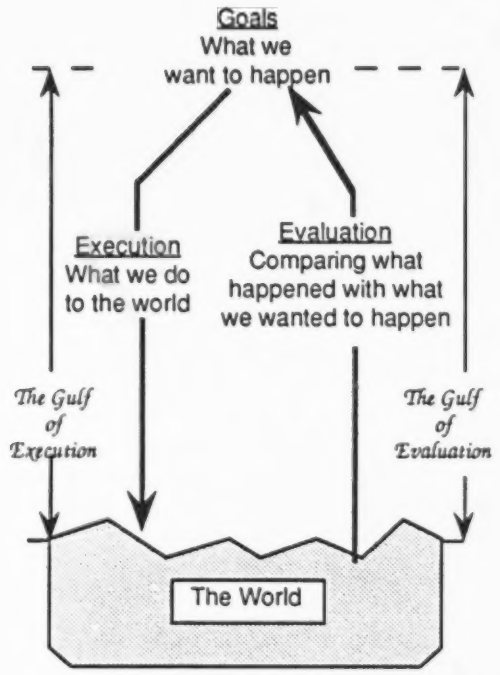

FIGURE 1. *The gulfs of execution and evaluation.* Each gulf is unidirectional: The gulf of execution extends from user goals to system state; the gulf of evaluation extends from system state to user goals. Every expression in the interface language has a meaning and a form. Semantic distance reflects the relationship between the user's intentions and the meanings of expressions in the interface language for both input and output. Referential distance reflects the relationship between the physical form of the expression and its meaning. The easier it is to get from the form of the expression to meaning, the smaller the referential distance.

Each gulf has two components of distance: *semantic distance* and *referential distance*.[1]

Semantic distance is the relationship between the user's intentions and the meanings of the expressions that are possible in the interface language. It refers to how well the interface language expresses the user's intentions. Can the user do what is intended with simple expressions or are complex chains of operations required? High-level programming languages can be seen as attempts to reduce semantic distance. The same argument applies to the evaluation side of action. Here, semantic distance refers to the amount of difference between the interpretation of the information available from the environment and the information needed to evaluate the environment.

Referential distance refers to the difference between the user's understanding of the meaning of an expression and the user's understanding of its form. Basically, when one decides to do a particular action sequence (that is, when one forms an intention to act), before the action can be done, its specific manner — its form — must be determined. To specify an action is to map from its meaning to its form. When the meaning and form are similar, the mapping can be simple (analogical) and the perceived referential distance is small.

When the form of an expression is unlike its meaning, the mapping is complex. Symbolic interfaces, for example, are typically high in referential distance because the relationships between the meaning of

[1] In the earlier work (Hutchins, Hollan, & Norman, 1986), *referential distance* was called *articulatory distance*. The name *articulatory* is unfortunate, however, for reasons that should become clear in the following discussion.

the expression (a symbolic expression) and the form by which it must be executed is arbitrary. The user must do the work to translate meaning to form. This work is the construction and maintenance of structure that spans the referential distance.

The same problem applies in reverse on the evaluation side of the action. Here, referential distance refers to the difference between the forms available in the environment and the meanings that are to be extracted from them. When form and meaning are similar (such as when an upward-moving line is to be interpreted as an increase in the value of the variable of interest), referential distance is small. When form and meaning are dissimilar or unrelated (as when the change in value must be computed from a series of numbers), referential distance is large.

Simple mappings between form and meaning occur when the form of the expression is similar to the meaning of the expression or when the structural relations among forms are similar to the structural relations among meanings. Consider the meanings of the words *left* and *right*. Now imagine two sets of expressions for these meanings, first, the words themselves — *left* and *right* — and second, some symbols — ⬅ and ➡. The first set, the words, has high referential distance because the form of the symbol *left* has little to do with the direction being indicated except by the arbitrary convention of the translation of letters to words and words to meanings. We think the relationship is "natural" only because we have learned it so well. But note what happens when we change languages to, say, Spanish or French: the physical form of the symbols changes dramatically (from *left* to *izquierdo* or *gauch*) while the meaning remains unchanged.

Now consider the pictorial symbols ⬅ and ➡. These symbols have a small referential distance. Notice that this is not because the symbol ⬅ has a structure similar to the meaning *left*. In fact, the structure of ⬅ does not inherently possess any meaning: Our understanding of it is entirely conventional and probably had to be taught upon first encounter. The claim to meaning similarity is "second order": The elements of the contrast set ⬅ and ➡ have a *structural relationship* to each other that is similar to the *meaning relationship* between the words *left* and *right*. It is the relationships that are similar. What matters is not the mappings between individual symbols and individual meanings (because that may be arbitrary), but rather the mappings between sets of symbols and sets of meanings.

We can illustrate the differences between semantic and referential distance by considering the results of an experimental comparison of two interfaces that have different interaction styles.

An Empirical Exploration of DM

In an empirical study of DM interfaces (Schustack, 19xx), users were given a task to perform using two drawing programs that were very different in style but with almost identical functionality. One of the interfaces had many features that should help reduce referential distance: For example, it was WYSIWYG (what you see is what you get), it provided instantaneous feedback on each action as it was performed, and all possible actions were continuously visually represented. It was mouse-driven, and it allowed the user to move around the picture space by analogous movements on the mouse pad. The other interface had none of these characteristics: Users wrote programming scripts in symbolic language, relying on their memory or the documentation to generate the elements and the syntax, and getting feedback on the syntactic acceptability of the entire script (and the resulting picture if the syntax is all correct) only after moving from script-editing mode to execution mode.

These interface differences affected the nature of the errors that users made, the relative difficulty of the various drawings, how long it took users to reach a criterion level of performance, and how well they exploited the more sophisticated features of the programs.

The visually oriented interface allowed users to complete the pictures significantly faster than the command-language style interface. This was a very robust finding that held up over the set of pictures as a whole (that is, the time to complete the series was significantly shorter for the visual-style interface), and it also tended to be true of the individual pictures. This global advantage in completion time occurred even if the time spent in initial document reading and practicing is excluded. Even though the users of the command-style interface spent more time on these preliminary activities before they even started copying the first picture, the copying task itself still took them substantially longer than it took users of the visual-style interface.

The first, very simple picture (which was a circle in the middle of the picture space) took users of the command-style interface about a half hour to complete, while the visual-interface users were finished in close to five minutes. Just getting enough control over the command-style interface to make it draw the simplest picture imposes a substantial burden on the new user. There was no such "start-up cost" apparent for users of the more visual interface—they showed no speed-up from the first to the second picture, while the command-style interface users brought their times down from the half hour it took for the first picture to about 10 minutes for the second.

But, even limiting the focus to simple quantitative measures, the situation is not all one-sided. Some of the pictures had characteristics that made them more quickly accomplished in one interface than in the other. In terms of time-to-completion, this effect not only reduced the speed benefit of the visual-style interface for certain pictures, but in a few cases reversed it to a speed benefit for the command-style interface. One of the consequences of the stylistic differences between the interfaces is that there are certain tasks that are quite well suited to the features of one interface and less well suited to the other. For example, the placement of labels (alphabetic strings) in a picture can be done quite easily in the command-style interface but is more cumbersome in the visual-style interface. For this task, the command-style interface clearly had less semantic distance than the visual-style interface.

The performances with the two interfaces also differed in the quality of the pictures produced (evaluated by rating eight independent dimensions of each copy produced). By and large, the copies produced were extremely good reproductions of the originals in an absolute sense. The pictures got an overall average rating of over 4.5 on a 5-point scale (where 5 represented perfect reproduction). There were two major characteristics of the quality of the pictures that are notable. First, the users of the command-style interface were overall significantly more accurate in their pictures, and were more accurate on every rated dimension on which there were any differences. The characteristics of the command-style interface made some aspects of fine-tuning fairly simple and straightforward (although not necessarily fast); in the visual-style interface users ran a substantial risk of ruining whatever version they already had in trying to make small changes. Thus, the command-style users were more willing to keep working until they were completely satisfied, whereas the visual-style interface users stopped when the picture was "good enough" (which was objectively quite good in most cases). Second, echoing the finding for the completion times above, there were certain pictures that were more suited to the strengths of each interface. Pictures

with features that were differentially easy to accomplish in the two interfaces showed differences between the interfaces in their accuracy (in both directions).

These results illustrate the importance of realizing that there is more to direct manipulation than short referential distance. On the one hand, the visual-style interface had low referential distance, but the problems subjects had in cleaning up rough drawings and placing text labels indicate it had high semantic distance with respect to some aspects of the tasks. The command-style interface, on the other hand, appeared to have high referential distance — the meanings of the commands were arbitrarily related to their form — but low semantic distance. With the visual-style interface, it was easy to specify something to do, but often difficult to specify just exactly what one wanted. With the command-style interface it was possible to specify exactly what one wanted, but difficult to generate the expression that would do it.

Everyday Listening and Auditory Icons[2]

An important method for enhancing directness is through appropriate feedback. This can be done visually or auditorily. Little is known about the role of sound in providing this kind of information. Part of our research efforts have examined the role of sound. The studies, conducted by Gaver, represent an attempt to understand how people listen to the world, and how such an understanding can help in developing auditory interfaces for computers.

Everyday Listening

There can be little doubt that sounds convey a great deal of information to listeners about events in the world. Yet relatively little attention has been given to how this happens. Instead, most studies of sound and hearing have been attempts to understand either how music is perceived, how the auditory system transduces sound, or how to measure and reduce environmental noise. There are, of course, notable exceptions to this rule (e.g., work on auditory streaming, localization, and speech), but on the whole, music, transduction, and noise seem to define the major interests in audition.

One large set of our studies were an attempt to define and explore a new way of understanding how people hear. In this research, we were concerned with understanding *everyday listening*, the act of gaining information about events in the world by listening to the sounds they make. He takes as a basic hypothesis that people *do* listen to events, and that they can obtain information about various aspects of these events by listening to them. From this beginning, he goes on to address two primary questions about these abilities: What do we hear?, and How do we hear it?

Work on a basic understanding of everyday listening is complementary to the development of auditory icons. On the one hand, the attributes of sonic events that may be mapped to attributes of events in the computer are suggested by an understanding of what we hear; and the ways to convey these attributes clearly to users are precisely the concern of research on how we hear. On the other hand, work on auditory interfaces is invaluable in testing the results of basic research in a more natural setting, and helps generate intuitions about everyday listening. Pursuing the basic and applied research together has proved to be a valuable course.

Auditory Icons

Though research on everyday listening is clearly only in its very early stages, already an application of this perspective on

[2] This section consists of edited excerpts from William W. Gaver's doctoral dissertation, "Everyday Listening and Auditory Icons."

audition has proved to be quite useful. This application involves using everyday sounds to provide information to computer users about events in the interface. When sounds are used in this way, the results are called *auditory icons* because of their similarities to visual icons.

Auditory icons hav ebeen described in three papers that discuss his work on auditory icons. First is the paper that introduced this idea (Gaver, 1986), and which lays the framework for further research in this area. Second is a technical report written recently for Apple Computer, Inc. (Gaver, 1988), which is a survey of current techniques for using sound, and which explores the issues involved in creating auditory icons in more detail. Last is a paper that describes the SonicFinder™, a prototype auditory interface developed by Gaver at Apple Computer, Inc. (Gaver, in press). This interface illustrates the use of auditory icons in an actual system.

These three papers show the development of auditory icons. In addition, the Apple technical report provides a broader view of how sounds can be used in interfaces, and the paper on the SonicFinder makes the ideas more concrete by providing specific examples of how auditory icons may be constructed.

Everyday Listening and Auditory Icons

A number of people have recently been exploring the possibilities of using nonspeech audio in interfaces (e.g., Bly, 1982; Mansur, 1984; Mezrich, Frysinger & Slivjanovski, 1984; Morrison & Lunney, 1985; Sumikawa, Blattner & Greenberg, in press). But our strategy behind auditory icons is considerably different from those used by other researchers, and has several advantages as a way of conveying information from computers.

The crux of the differences between auditory icons and other methods of using sound is that auditory icons are based on an understanding of everyday listening, while other techniques rely on musical manipulations of sound to convey data. This has crucial effects on the kinds of mappings between sounds and information that can be created using these strategies. Because the attributes of everyday listening are those of sound-producing events, a nomic or iconic mapping can hold between auditory icons and events in the computer. Systems that rely on musical manipulations of sound can only employ metaphorical or symbolic mappings. Because of this difference, auditory icons are likely to be more intuitively obvious to users, more easily learned and remembered, and more likely to increase users' feelings of working directly in the task domain, rather than on a computer.

It is important to note here that the promise of auditory icons is entirely based on the way of understanding "everyday listening." That such a new area of research should prove so fruitful is heartening: The appeal of auditory icons must be taken as support for the notion of everyday listening.

In addition, work on everyday listening and auditory icons is intimately related. Auditory icons depend on an understanding of everyday listening so that computer events can be reliably and usefully mapped to sound. Conversely, work on auditory icons can help provide hypotheses and evidence for research on everyday listening. Finding useful auditory icons often makes apparent interesting issues about what events people hear, issues that may lead to productive empirical examinations. In this way, work on auditory icons supplements studies of physics, protocol studies, and more rigorous experimental work in helping to understand everyday listening.

COGNITIVE ARTIFACTS

As we studied direct manipulation systems and contrasted them with command-language systems, we became aware that the questions really focused upon a more

general concern: the manner by which people interact with the world. This takes on special concern with computer systems, for with the computer, there is only a second-order interaction with the world. The computer contains a representation of objects and information in the world and the interaction is done upon this representation. The indirectness leads to the gulfs that we identified in our earlier studies. And the indirectness leads to both the power and the difficulty of the interaction. The major feature of a direct manipulation interface is its attempt to minimize the indirectness by minimizing the distinction between the appearance and requirements of the representing world of the computer and the external, physical world — the represented world. Still, direct manipulation interfaces are really only one example of a more general issue: the study of artificial systems in general and, especially, the characteristics of artifacts that aid human cognition.

Most artifacts aid physical requirements and enhance physical abilities. Some artifacts, however, increase our cognitive abilities: We use the term "cognitive artifacts" to refer to these objects. Although cognitive artifacts are less numerous and less well studied than physical artifacts, they play an increasingly important role in our lives. Maps, drawings, blueprints, lists, tables, calendars, books, slide rules, calculators: These are all examples of cognitive artifacts. Computers are a special class of artifact and they deserve special treatment, for they can do things that are difficult or impossible for other artifacts. Still, they are artifacts, and an understanding of the psychology of our interaction with things must be relevant to our interactions with computerized things.

Computational Power in Artifacts

The computer can function as a powerful and independent information processing device. As a result, we often concentrate upon its power to do tasks previously done by humans, and then view the problem of human computer interaction (HCI) as one of specifying a division of labor between human and computer and designing a communication protocol that can be used to coordinate the efforts of the two participants. This is, of course, an important possibility for HCI, but it is not the only one, and assuming it prematurely may lead one to overlook some other important aspects of interactions with artifacts in general and computers in particular.

Our view of cognition assumes neither that cognition happens all "in the head" nor that useful cognitive artifacts necessarily achieve their results by augmenting or amplifying the cognitive abilities of users. Instead, we look for the power of cognitive artifacts in the interaction of what is inside the person and that which is outside the person.

Checklist as Cognitive Artifact

One simple (noncomputer) artifact that we have examined in some detail is the simple checklist, used to organize tasks whenever it is essential that a list of actions all be performed, oftentimes in particular order (Hutchins, 1986). The checklist organizes the behavior of the task performer in a way that may not be possible for the unaided performer. In order to use a checklist as a guide to action, the task performer must coordinate with both the checklist and the environment in which the actions are to be taken.

Achieving coordination with the checklist requires the actor to invoke procedures for the use of the checklist. These include reading skills and a strategy of sequential execution that permits the task performer to ensure that the steps will be done in the correct order and that each step will be done once and only once. The fixed linear structure of the checklist permits the user to accomplish this by simply keeping track of an index that indicates the first unexecuted (or last executed) item.

While the task performer is following the checklist, high-level control of task-related behavior is given to the structure of the artifact. It might seem that the actor alternates coordinating with the structure of the checklist and coordinating with the structure of the task world. However, the coordination with the two media is in fact simultaneous to the extent that understanding a step in the description may depend upon understanding the state of the world in which it is to be carried out. The experience of the meanings of the descriptions of the steps incorporates experience of the task world, and the doing of the actions in the task world incorporates the experience of the meaning of the task steps. The importance of this is that in this mediated performance, the person provides continuous coordination among several structured media, some internal, some external.

It is easy to show that a novice task performer has no internal representation of the entire checklist. The large-scale structure of the task performance is in the organization of the checklist, not in the mind of the task performer. With practice, of course, the novice may learn the procedure and the large-scale structure of the task may come to be represented in the mind of the performer. As was the case with the typewriter keyboard, internalizing such structure may lead to much more rapid and efficient performance. That, however, is another story. At this point in our argument we wish only to illustrate the fact that people can make use of structure in their environment to transform their cognitive abilities without having any enduring internal representation of that structure.

Problem Solving as Re-Representation

Cognitive artifacts, whether computerized or not, are always vehicles for representations of the problems they are used to solve. The way a problem is represented can radically change what is required of the problem solver and a good artifact will, therefore, use representations that match those of their users. In fact, Simon has suggested that "solving a problem simply means representing it so as to make the solution transparent" (Simon, 1981, p. 153). Many artifacts can serve as representational transformers, taking the representation of the problem from one format into a format better suited for use by people.[2]

Five Ways to Do Distance/Rate/Time Problems

An example from Hutchins's (in press) study of ship navigation demonstrates how the structure of representational artifacts can change the cognitive activities required to do a task. Imagine a navigator who has just plotted a position fix and needs to compute the ship's speed based on the distance the ship has moved in the interval of time that elapsed between the current fix and the previous one. This is a standard distance/rate/time problem. For this particular exercise assume that the two fix positions are 1,500 yards apart and that 3 minutes of time have elapsed between the fix observations: What is the ship's speed (in knots)?

Consider the cognition required under five different conditions:

> *Condition 1:* The performer has the following resources: paper and pencil, knowledge of algebra, knowledge of arithmetic, knowledge that there are 2,000 yards in a nautical mile and 60 minutes in an hour, and knowledge of the equation $D = RT$.

[3] Hill (1988) argues that artificial intelligence serves primarily as the developer of representational vehicles that permit the human intellect to express itself in ways more powerful than previous methods; more powerful in the sense that they match better human capabilities and structures.

Condition 2: The task performer has the same resources as in Condition 1, except that instead of a paper and pencil, the task performer has a four-function pocket calculator.

Condition 3: The task performer has a three-scale nomogram (see Figure 2) and knows how to use it.

Condition 4: The task performer has a nautical slide-rule (see Figure 3) and knows how to use it.

Condition 5: The task performer has no material implements at all, but knows how to use what navigators call the "3 minute" rule.

In Condition 1 (paper and pencil), the task performer will first have to use the knowledge of algebra to manipulate the formula $D = RT$ to the form $R = D/T$ so that rate can be solved for directly from the given values of D and T. The distance in yards will have to be converted to the equivalent number of miles (requiring knowledge of the number of yards in a mile and the relevant arithmetic). The time in minutes will have to be converted to the equivalent number of hours (requiring knowledge of the number of minutes in an hour and, again, arithmetic). The distance measure must be divided by the time measure (requiring arithmetic again) to get the rate. Of course, these things can be done in a different order; for example, the division could come before either of the unit conversions, or between them, but in any case all these things must be done at some point in order to solve the problem.

D = RT
R = D/T
1500 yards = 1500/2000 = 3/4 miles
3 minutes = 3/60 = 1/20 hours
R = (3/4) 20 = 15 knots

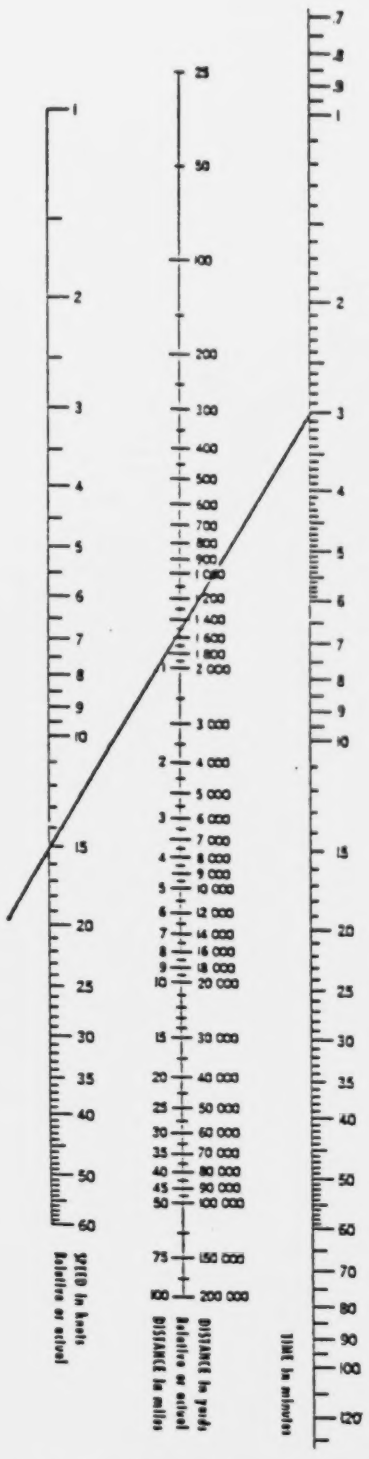

FIGURE 2. The time/distance/speed nomogram.

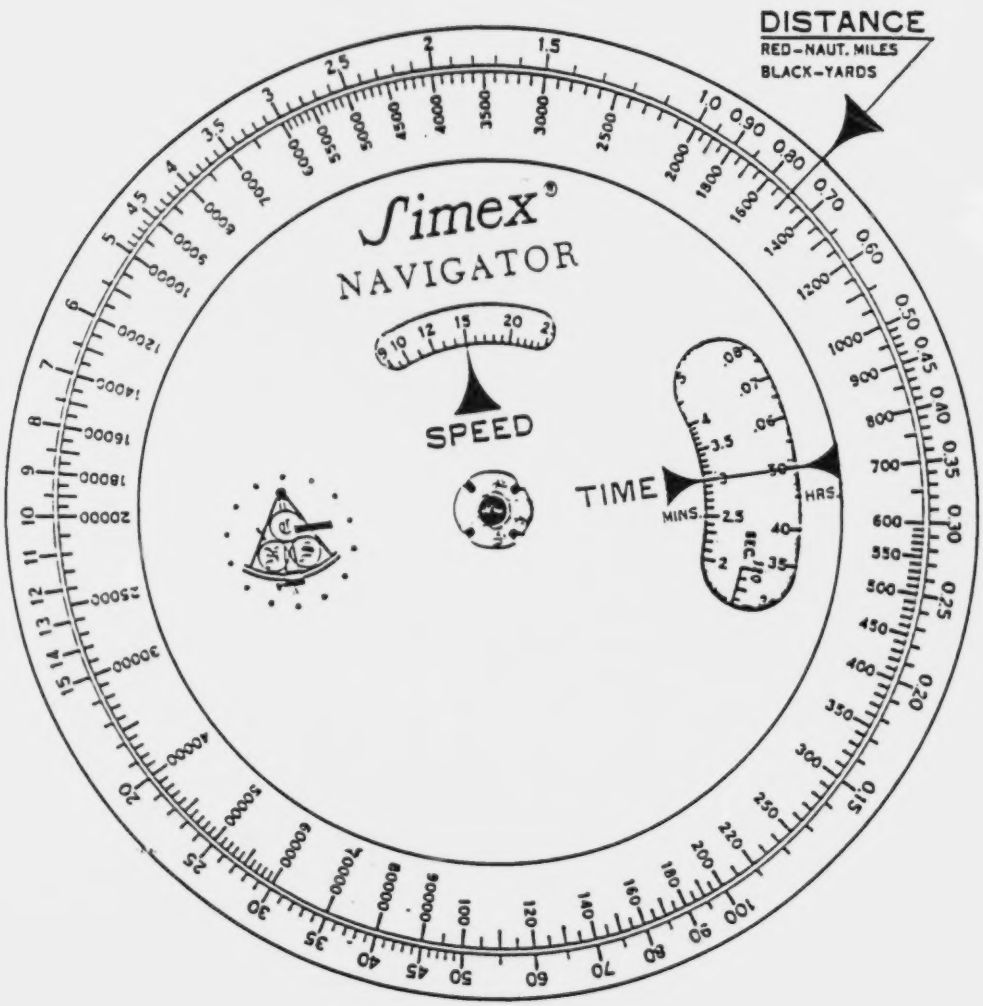

FIGURE 3. Navigation slide rule.

Although the arithmetic and algebraic skills required to solve this problem are reasonably simple, they would tax the abilities of many navigation practitioners in the navy. The problem is not that the arithmetic is difficult, but rather that it is necessary to figure out what to do and how to fit the intermediate steps together while in the real, operational setting of time and social pressures and task demands. One may be perfectly capable of doing every one of the component subtasks in this problem, but fail completely for lack of ability to organize and coordinate the various parts of the solution with each other.

In Condition 2 (the calculator), the procedures for doing the arithmetic operations of division and multiplication are restructured so that instead of decomposing the problem to a set of operations on paper, values are keyed into the calculator and buttons pushed. Depending upon the order in which the steps are taken, it may be necessary to remember a previous result and

enter it into a later operation, after other operations have intervened. This version of the task would probably also tax the abilities of many navigation practitioners, because the hard part is not doing the arithmetic but in deciding how to coordinate the arithmetic operations with each other. The calculator gives no support for that part of the task.

Conditions 1 and 2 (paper and pencil and calculator) are alike in that they use general computational knowledge which gives little help in structuring the actions. Because of this, the computation is complex, and it contains many steps, especially if we count as a step the writing of each symbol or each key press of the calculator.

Now consider Condition 3 (the nomogram). A nomogram is a printed form containing scales, usually linear or logarithmic, so arranged so that a straight line drawn through the known values on the scales intersects the other scales at the solution points. In the case of this navigation problem, there are three logarithmic scales: one for rate (usually calibrated in knots), one for distance (usually calibrated in both yards and nautical miles), and one for time (usually calibrated in seconds, minutes, and hours). A straight line through any two known points on any two scales intersects the third scale at whatever value solves the $D = RT$ equation. Thus, to solve the particular problem under discussion, one simply makes marks at 3 minutes on the time scale and at 1500 yards on the distance scale. Then one draws a line through those two marks with a straightedge: The answer of 15 knots can then be read on the speed scale where the drawn line intersects the scale. This procedure is easy for everyone, and well within the limits for navigation practitioners in the navy.

Of course, Condition 3 has an unfair advantage over Conditions 1 and 2. The hard work was done in making the nomogram in the first place. But that is part of the point. This is a very frequently occurring problem, and this tool is designed specifically to make its solution easy.

Condition 4 (the nautical slide rule) provides an analysis similar to that of Condition 3: A slide rule is simply a generalized, mechanical version of the nomogram, where the movement of the scales and of the sliding hair line corresponds to the setting of the points and the drawing of the line on the nomogram. In this case, one aligns the distance index with the desired distance on the distance scale, aligns the elapsed time index with the desired time on the time scale, and then the speed index points to the speed in knots.

In both the nomogram and the slide rule, having the scales in the units normally encountered eliminates the need to convert one kind of unit into another, but much more important is the fact that these two conditions eliminate the need for any knowledge of algebra. The nomogram and slide rule transform the task from one of computational planning — figuring out what to divide by what — to one of simple manipulation. In the first two conditions, knowledge of the numbers and the equations provide little assistance in knowing exactly what to do. When using the nomogram or the slide rule, the structure of the artifacts themselves make it almost impossible to fail: Just enter the knowledge known into the device and it provides the value for the missing term. The relations $D = RT$, $R = D/T$, and $T = D/R$ are *built into* the structure of the nomogram and slide-rule.

With the proper artifact, although the task performer still needs to know something, the knowledge that is required is less complicated and less general than that required with just paper and pencil or calculator. What needs to be done can be inferred from the structure of the artifacts themselves. They constrain the task so that many errors that are easy (and frequent) with pencil and paper or calculator are not even possible with the artifact. Much of the

computation is done by the tool (or by the designer of the tool). The person can get by doing less because the tool does more.

But now consider Condition 5, the use of a specialized internal artifact. A general computation rule (the 3-minute rule) is that the number of hundreds of yards a ship travels in 3 minutes *is* its speed in knots.[4] In our problem the ship traveled 1,500 yards in 3 minutes, so we instantly "see" that its speed is 15 knots. The navigator need only remove the last two digits from the distance in miles: *Voila!* 15.

Now the reader may really cry "foul play." "This is a special example with special, made-up numbers that permit this trick to be used," you might say. True, but because the rule is so simple, navigators try to determine distances in yards every 3 minutes. Navigators are capable of measuring their distance every 2 minutes or even every minute, but three minutes is more common, not because it meets the needs of the ship better than the other intervals, but because it meets them well enough, and it makes this computation so convenient.[5]

Artifacts — Amplifiers or Transformers of Cognition

It has now become commonplace to speak of technology, especially information processing technology, as an amplifier of cognitive abilities. Cole and Griffin (1980) show, however, that the appearance of amplification is an artifact of a commonly assumed perspective. When we concentrate on the product of the cognitive work, cultural technologies, from writing and mathematics to the kinds of tools we have considered here, appear to amplify the cognitive powers of their users. Using these tools, people can certainly do things they could not do without them. When we shift our focus to the process by which cognitive work is accomplished, however, we see something else: Cognitive abilities of unchanged power are reorganized in interaction with the structure of the technology.

There are two important things to notice about these alternative ways to do an algebraic task. First, the very existence of these five different ways is evidence of a lot of effort directed toward avoiding the use of algebraic reasoning, and arithmetic. Second, these tools and techniques permit the task performer to avoid doing algebra, reasoning and arithmetic, replacing these activities with aligning indices on scales, or simply deleting zeros from numbers. These tools transform the task by mapping it into a representational medium in which the method or answer is apparent.

Note that the required procedures may be trivial, but they are not obvious. One can scarcely imagine a simpler procedure than the application of the 3-minute rule, yet many who use it have no idea why it works and would never have discovered it on their own. We return to this point later.

Let us now summarize the argument so far. The power of cognitive artifacts derives from the fact that they form or transform cognitive tasks. An artifact that transforms a task can radically change the kind of mental structure that is required to bridge the gap between user intentions and actions on the device interface (the world). They also create entirely new relationships to the world. A cognitive artifact that transforms tasks reduces semantic distance by simplifying what must be done to solve a problem. This is very clear in the case of navigation instruments that replace

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[4] One hundred yards is 1/20 of a nautical mile and 3 minutes is 1/20 of an hour. So the number of hundred yards traveled in 3 minutes is the number of miles that will be traveled in 1 hour, which is the speed in knots.

[5] The nautical slide rule and nomogram are normally only used when the ship is away from land and the fix intervals are much longer than 3 minutes. When the cycle is performed on the shorter intervals of 1 or 2 minutes, speed is normally computed by conversion to the 3-minute standard. For example, if the ship travels 800 yards in 2 minutes, it would travel 1200 yards in 3 minutes, so its speed is 12 knots.

algebraic and arithmetic operations with simple manipulations of external or internal structure. Even the simple checklist reduces the semantic distance for its user. Lacking the checklist, the novice must discover the steps that need to be done and an order in which they can be applied. With the checklist, the task is transformed: reading and following instructions take the place of procedural reasoning.

The Cottage Cheese Story

In a study of weight watchers in Southern California, de la Rocha reports[6] the following strategy is employed by a weight watcher. The menu for the meal calls for 2/3 of a cup of cottage cheese, but the dieter only wants to make 3/4 of the recipe amount. How can the dieter computer the proper amount of cottage cheese? In the case reported, the person filled a measuring cup up to the 2/3 mark with cottage cheese, dumped the measured cottage cheese on a plate, patted it out into a pancake, drew an X on the top that divided it into four "pie sections" of equal size, and then used three of the four sections.

The recipe provides an initial set of symbolic constraints, but instead of operating on the symbolic representation, the representation was interpreted into the physical medium of cottage cheese. This provided a mapping of the symbolic statement of the problem onto manual action in the physical world. In reviewing this and related examples of real world arithmetic reasoning, Resnick (1987) notes:

> They got reliable arithmetic results by treating the material they were working with as part of their calculation process, rather than by just operating on symbols. (p. 14)

To do the task symbolically, one would have to multiply the fractions together. One way to do that would be to notice that the 3 in the numerator of 3/4 cancels the 3 in the denominator of 2/3, giving 2/4, which is easily transformed to 1/2. The operations are easy for one experienced with the relevant arithmetic, but if one just thinks about the problem it has the potential to be difficult (taking 3/4 of 2/3 seems hard, something like, perhaps the taking of 5/7 of 8/9). Moreover, the arithmetic proceeds according to syntactic rules that respond to the *form* of the expression and have nothing whatever to do with cottage cheese. Only after the syntactic operations have been completed, is the new symbolic form, 1/2 cup, interpreted in the world of cottage cheese. It is the sensitivity to form rather than meaning and the suspension of interpretation during syntactic operations that makes it a formal system. Formal systems are thus liberated from the constraints of concrete reality. But the gain in power is at the expense of clarity.

The theme of liberation from constraints of concrete reality is prevalent in the philosophical and developmental literature, and the history of Western civilization is full of demonstrations of the enormous power of formal systems. Yet, this poses a computational burden on people in the requirement for syntactic knowledge and mediation of the formal operations: We call this the burden of syntax.

As observers and actors we may certainly intend what we do in the world and interpret the consequences. But the world itself neither interprets nor intends consequences. We take the point of view of an observer, interpreting actions and states: The world is a system with neither representations nor interpretations — the world simply responds (this view is presented in expanded form in Gaver, 1988). Thus, although our actions have meaning to us and to other observers, they do not to the world. The notion of "the meaning of an expression" is a linguistic notion. It implies

[6] This account originally appeared in a chapter by Lave, Murtaugh, and de la Rocha (1984).

a reference gap — a relationship between one thing and some other thing that it "represents" or "stands for." The reference gap in turn implies an interpreter, an agent that can bridge the gap and make a mapping from the expression that does the representing to the thing that is represented. This reference gap does not exist for events in the world. It occurs only when there are symbolic relations. This difference of perspective provides two apparently incompatible realms: a realm of action and objects and a realm of symbols. Computers provide us a way to put these two together, but it is difficult to describe from the perspective of either realm.[7]

From the perspective of the symbolic realm, we want the expressions in the interface language to be composed of the objects and actions in the world of interest. From the perspective of the realm of actions and objects, we want the objects and actions in the world to be the elements of the symbolic expressions that refer to them. The key to the sensation of directness is that technology permits the design of an interface-language/model-world that can approximate this state of affairs to an extent impossible in any previous medium.

By presenting the world of action as the interface language itself, we can collapse the symbolic reference gap. And if the model world is properly designed, it can be the kind of artifact we sought. Consider a system like the Macintosh where files are removed by dragging icons that represent them to the trash can. From the point of view of our analysis, what is especially nice about this interface is that the physical constraints of the world of file icons make certain classes of syntactic errors impossible: It is not possible to try to remove a file that does not exist. [8]

The Design of Appropriately Constrained Artifacts

The symbolic world is an artificial world. If syntax were the only constraint, the protection against the impossible and the nonsensical is weak because it places a heavy burden on the knowledge of the user and the correctness of the operations.

The weight watcher had two means to solve the problem — by manipulating symbols or by manipulating the cottage cheese. The culturally valued technique (taught in schools) is to do symbolic manipulations on the symbolic representations. The preferred technique of people is to manipulate the actual objects.

Given this apparent conflict between cultural and individual preferences, there are at least two roads to take. One is to mechanize the manipulation of symbolic structures. That road leads to the computer. Another is to stay in the world of manual manipulation. This second road leads to a special class of computational artifacts in which the syntax of the represented domain is built into the physical properties of the representing object. But how can we get syntactic constraints out of physical properties?

Locking the door to your car with the keys inside is an annoying error. One could imagine a checklist for leaving the car that could prevent this sequence error, but then the checklist would be a nuisance and would likely often be skipped. There is,

[7] Gaver (1988) describes exactly this dichotomy, but in the context of distinguishing between cognitive and ecological (Gibsonian) views of psychology. Gaver's work provides a valuable step in the argument we present here.

[8] Unfortunately, the collapse of the reference gap is never complete. There is still the mouse protocol and the key presses instead of getting our hands on the objects. Even touch screens leave a gulf. And the objects of interest may or may not actually be the object of interest. What the object of interest is may depend upon the user's goals at any moment.

however, an infallible way to ensure that keys are not locked in the car. That is to make the car door so that it can only be locked with the key operated from the outside. Norman (1988) called this type of scheme a "forcing function," for it provided a physical constraint so that failure at one stage prevents the next step from happening.

Sequential dependencies among actions imply a kind of syntax of action. Doing the action in one order is a well-formed action, and violating sequential dependencies produces a malformed action. But sequential relations are only one kind of relation that can be constrained. There are other sorts of syntax of action. Inserting a disk upside down or backwards in the disk drive is a "syntax" error that can be eliminated by designing disks and drives with physical constraints that make only meaningful actions possible. Now let us see how to carry this method to the design of artifacts so that physical constraints preclude erroneous actions.

Intelligent artifacts are "representing worlds": That is, they form a representation of some aspect of the external, physical world and do their operations upon this internal, *representing* world. If the artifact is to be readily usable, the constraints of the representing world must have a meaningful relationship to the constraints of the represented world. Furthermore, there must be a reason to do things in the artifact rather than directly in the world — why manipulate the representation if one can manipulate the real thing? In the case of mathematics, the reason is often that some important aspect of the represented world cannot be directly operated upon. In the case of the cottage cheese example, the manipulations of the real object are messy, although still do-able: Other kinds of objects are not apt to be as susceptible to manipulation. In the case of computing the speed of the ship, no physical manipulation will do the trick — symbolic, numeric computation is required.

If a representing world is necessary, the design question for the artifact, then, is how to achieve the appropriate constraints in the representing world so that all possible actions model meaningful actions in the represented world (and so that nonmeaningful actions are not possible).

Some artifacts, such as the nomogram, exploit the fact that they are physical as well as symbolic. The usual analysis of symbols ignores the fact that symbols are also physical things: The physical properties are thought to be irrelevant to their symbolic, computational, or representational properties. Certainly, the manipulation of the symbols has nothing to do with the constraints of the domain of interest. In fact, for many purposes the symbols need not be thought of as things at all. Instead, they are treated as if they exist in their own realm, separated from the realm of "real" things. External representations of arithmetic are thought to be helpful only because they ease memory load, not because there is anything in the physical structure of their external representation that is essential to the computation.

The O-Symbol

We now have on hand the conceptual pieces required to construct the new kind of artifact. First, select the objects that are to serve as the symbols in the system: Note that these are both objects and symbols — they are *o-symbols* (object-symbols) These o-symbols serve as the interface between the world of objects and the world of symbols, each being simultaneously in both the world of objects and of symbols. Now, in the world of objects, the items can exploit the powers of forcing functions, using physical constraints in such a way to force the symbolic interpretations to be meaningful.

The nomogram for computing boat speed (Figure 2) was constructed in this way. The physical constraints for the layout of the logarithmic scales (which are the symbolic representations for speed, distance, and time) make certain classes of syntactic errors impossible.

Reinterpreting the Attraction of Direct Manipulation Interfaces

We are now able to return to the problem area that triggered this investigation: the study of direct manipulation interfaces. Consider what one wants in an artifact: One wants structures that simplify the task for the person, that permit new computations, or that produce new interpretations, all easier, faster, and more accurately or precisely than could be done without the artifact. And a major enhancement of the artifact comes when it is so constructed that one can't do wrong, where the structures by their very construction are incapable of producing syntactic violations. This, we believe, is what is at the heart of the attractiveness of direct manipulation interfaces to computers.

True, DM interfaces have another attraction: the naturalness of the mappings between the represented and representing worlds. But this very naturalness also provides an opportunity to be exploited by making the manipulations of the representing world follow the physical constraints of the represented world. This is one reason why the visible file folders metaphor for organizing computer files can be so appealing. But it is not just any representing world that works this way: DM works when the physical constraints of manipulating the representation prevent it from representing anything nonmeaningful or impossible.

We have now considered several modes of computation that turn out to fill the four spaces of a two-by-two array: One dimension represents the kinds of constraints — syntactic or physical; the other dimension represents the kind of action done by the artifact — passive or active. The combination gives the four computational modes that are shown in Figure 4.

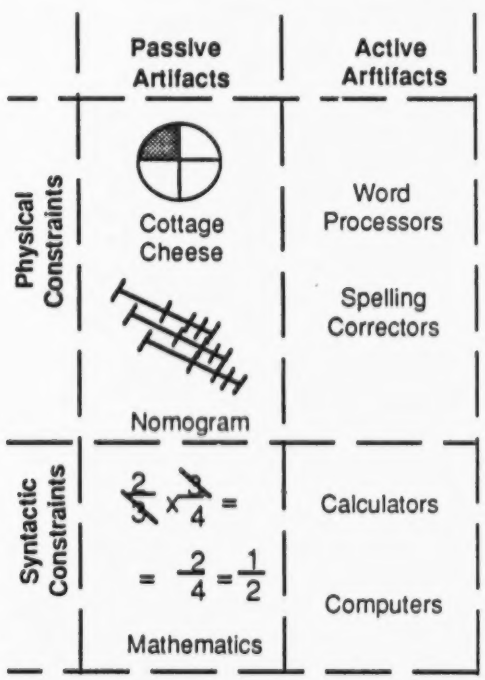

FIGURE 4. Four modes of artifacts.

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Appendix: Draft Checklist for the Design of an Artifact

It is tempting to use the analyses of this report as design rules. This operation is premature for the full understanding of cognitive artifacts and, in particular, the o-symbol, do not yet exist. Nonetheless, it is possible to provide a draft checklist of design procedures that follow the principles studied in this research project. The principles include those discussed in this report plus the analysis of human action into seven stages of action (Norman, 1986, 1988) and an emphasis on the proper role of constraints, affordances, and mappings (Norman, 1988). This checklist needs elaboration and verification, but it illustrates how the work conducted under this research contract could be applied to the design setting.

1. Do a task analysis.
What needs to be done?
What are the variables to be controlled, to be determined?
What operations or actions need to be controlled?
What feedback is needed to the user?
What errors are possible?

2. Do a system analysis.
Where does the task fit in the general overall picture?
How do the various participants interact with one another?
What are the hidden goals of the task?
If the task or method of doing the task changes, what side-effects result in the rest of the organization?

3. Select the o-symbols.

4. Do the design.
Develop the forcing function.
Make operations visible.
Make results visible.
Get the affordances right.
Follow the seven stages as design guides.

5. Redo the task and system analysis.
Are all meaningful operations possible?
Are all nonmeaningful operations impossible?
What kinds of social interactions are supported? What kinds are made more difficult?
Does the user operate directly on the o-symbols?
Are the affordances right—does the first-time or casual user need extra guidance?
Is the feedback right? Can the user tell what has been done?
How are errors:
- Discovered?
- Recovered from?
- Corrected?

6. Watch typical users in a realistic situation.
Can they use the artifact appropriately?
Do the o-symbols work properly—are they interpreted properly?
Does the artifact fulfill the design goals?
Do they wish to use the artifact in ways not fully supported, such as:
- For repeated operations, keeping some previous values?
- In a different order than contemplated?
- For a different purpose?
- Etc.

And, if so, does the design support these needs?
Do they make errors?
Do they discover all their errors?
Can they recover (gracefully) from error?
Would they stop their current methods and switch to the artifact?

7. Repeat design effort from 2, with emphasis on all "no" answers, to 6.

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